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Evaluating Phenological Indicators for Predicting Giant Foxtail (*Setaria faberi*) Emergence

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We evaluated the use of ornamental plants as phenological indicators for predicting giant foxtail emergence and compared their performance with predictions based upon Julian day, cumulative growing degree–days (GDD), and the WeedCast program. From 1997 to 2001, we monitored giant foxtail emergence in a field experiment with and without fall and spring tillage to estimate the dates of 25, 50, and 80% emergence; we also recorded dates of first and full bloom of 23 ornamental plant species. Dates of weed emergence and ornamental blooming for 1997 to 2000 were compiled in a phenological calendar consisting of 54 phenological events for each year, and events were ordered by average (1997 to 2000) cumulative GDD (January 1 start date, 10 C base temperature). Bloom events occurring just before the giant foxtail emergence events were chosen as the phenological indicators for 2001. The Julian day method used the average (1997 to 2000) dates of foxtail emergence to predict 2001 emergence. The GDD model (October 1 start date, 0 C base temperature) was chosen by determining the combination of start date and base temperature that provided the lowest coefficient of variation for the 1997 to 2000 data. The WeedCast prediction was generated using local soil and environmental data from 2001. The rank order of the 54 phenological events in 2001 showed little deviation from the 4-yr (1997 to 2000) average rank order ($R^2 =$ 0.96). The phenological calendar indicated that, on average, 25% of giant foxtail seedlings had emerged when red chokeberry was in first bloom, and 80% of seedlings had emerged around the time multiflora rose was in full bloom. We compared the phenological calendar predictions for 25, 50, and 80% emergence with those based on Julian day, cumulative GDD, and WeedCast. The average deviation in predictions ranged from 4.4 d for the phenological calendar to 11.4 d for GDD. In addition to being generally more accurate, the phenological calendar approach also offers the advantage of providing information on the order of phenological events, thus helping to anticipate the progress of emergence and to plan and implement management strategies.

Nomenclature: Giant foxtail, *Setaria faberi* Herrm. SETFA.
Key words: Seedling emergence; phenology; emergence prediction; growing degree–days.

The timing and progression of seedling emergence are important determinants of weed competitiveness, susceptibility to control measures, and reproductive success (Blackshaw et al. 1981; Forcella et al. 2000). The ability to time field operations (e.g., land preparation, fertilization, planting) and weed control efforts (chemical, mechanical, biological) with respect to environmental conditions (rainfall and soil warming) can determine the effectiveness of weed management. One of the fundamental principles of integrated pest management (IPM) is that precisely timed monitoring (i.e., scouting) and application of control tactics to the most susceptible stages of weed development can help reduce herbicide use by increasing the effectiveness of chemical, mechanical, and biological methods of weed control (Norris et al. 2003). Properly timed control tactics reduce the cost of managing weeds and decrease the potential for yield reductions from increased weed competition or crop injury (Forcella et al. 1993).

Patterns of emergence in relation to rainfall, cultivation, tillage system, and time have been described for several species, with results that vary among years and management systems (Cardina and Hook 1989; Ogg and Dawson 1984; Roberts and Feast 1970; Roberts and Potter 1980). Attempts to use GDD alone in models that would be generally applicable, such as have been useful for predicting insect phenology (Akers and Nielsen 1984; Higley et al. 1986; Preuss 1983), have had mixed success in providing the level of accuracy needed for useful predictions of weed emergence (Carberry and Campbell 1989; King and Oliver 1994; Stoller and Wax 1973; Webster et al. 1998). Other empirical models have used meteorological variables (mostly temperature and soil moisture) to predict the probability of emergence (Grundy and Mead 2000).

Mechanistic models that describe environmental effects on distinct processes involved in emergence, i.e. seed dormancy alleviation, imbibition, germination, and seedling elongation, have provided a useful approach for predicting weed phenology (Forcella et al. 2000). For example, Roman et al. (2000) developed a model for predicting common lambsquarters (*Chenopodium album* L.) emergence that uses hydrothermal time to describe germination and thermal time to describe shoot elongation. Dekker et al. (2003) extended this approach by including soil oxygen levels in a measure of "oxyhydrothermal time" to predict afterripening, dormancy reinduction, germination, and seedling emergence in various foxtail (*Setaria*) species. One practical approach to weed emergence simulation is the WeedCast model, which accumulates units of hydrothermal time from soil temperature, when soil water potential is above a base value (Archer et al. 2001; Forcella 1998). This model has been adapted for simulation of weed emergence in several species (Ekeleme et al. 2005; Forcella 1993; Harvey and Forcella 1993; Masin et al. 2005).

As mechanistic models of seedling emergence have become increasingly sophisticated and more accurate, the environmental data and computational resource demands have increased. Models that divide emergence into distinct processes require more information on how microclimate and management variables interact to determine the rates of each of several processes (Forcella et al. 2000; Vleeshouwers and Kropff 2000). As model sophistication increases, the utility

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Table 1. Time of tillage, herbicide, and soybean-planting operations for giant foxtail emergence study from 1997 to 2001.

Year	Fall Tillage	Spring Tillage	Spring Burndown[a]	Soybean Planting
1997	10/9/96	4/30/97	5/2/97	5/5/97
1998	11/24/97	3/30/98	4/28/98	5/7/98
1999	11/4/98	4/7/99	4/24/99	4/29/99
2000	10/15/99	4/14/00	4/14/00	4/17/00
2001	10/16/00	4/20/01	4/27/01	4/30/01

[a] Glyphosate applied at 0.84 kg ae ha^{-1} with a conventional broadcast sprayer to plots that were not tilled in spring.

and application of mechanistic models for growers become limited by the difficulty in collecting the necessary environmental data.

For many years, phenological indicators have been used to predict pest activity, with recorded observations that date back to at least the 18th century (Huberman 1941). Phenological indicators are corresponding phenological events that are easily observable and precisely timed and include insects, flowering trees, or other organisms that respond to and integrate the same or similar environmental stimuli that drive the biological process of interest (Herms 1990; Huberman 1941; Kapler 1966; Mussey and Potter 1997). Plant phenology has been shown to accurately predict insect and mite activity for many species representing different life histories (Herms 2002, 2004; Kapler 1966; Mussey and Potter 1997).

Because the development of plants is temperature dependent (Rathcke and Lacey 1985), the easily observed phenology of ornamental plants might also be helpful for tracking the environmental factors that affect weed phenology. If the blooming period of ornamental plants can be shown to correspond with the seasonal appearance of important weed-emergence stages, the easily monitored phenological sequence of bloom times could be used to predict the order and duration of those emergence stages.

We have been exploring the use of phenological indicators for predicting weed emergence. The objective of this study was to evaluate the use of a phenological calendar based on flowering phenology of ornamental plants for predicting emergence phenology of giant foxtail. This species is the most widespread annual grass weed in corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr] production throughout the north-central United States (Dekker et al. 2003). Here, we describe our protocol for developing an ornamental-plant phenological calendar that incorporates weed emergence data for the 1997 to 2000 growing seasons to predict observed emergence events in 2001. We then compare the accuracy of the predictions based on the phenological calendar with predictions based on Julian day (JD), cumulative GDD, and the WeedCast model.

Materials and Methods

Giant Foxtail Emergence Experiment. Weed seedling emergence studies were conducted from autumn 1996 through the summer of 2001 in a 1-ha field at the Ohio Agricultural Research and Development Center (OARDC) near Wooster, OH (81°56′W, 40°42′N; elevation 310 m). Soil at this site is classified as a fine, mixed, Typic Fragiaqualf (Luvisols) of the Canfield series, which is a deep, gently sloping, moderately to well-drained silt-loam soil with a relatively impermeable fragipan at a depth of 40 to 75 cm. The soil has 11% sand, 75% silt, and 14% clay, with 1.9% organic matter. The climate is continental; annual precipitation averages 905 mm. The average minimum (January) and maximum (July) temperatures are −4.8 and 29.2 C, respectively. The field had been in a corn–soybean rotation for 3 yr before initiating the study and contained a natural infestation of giant foxtail.

A 2 by 2 factorial experiment was conducted in a randomized complete-block design with 5 replications. The two factors were fall tillage (±) and spring tillage (±); thus, plots received either fall tillage only, fall tillage plus spring tillage, spring tillage only, or neither fall nor spring tillage. Tillage consisted of a single pass with a chisel plow followed immediately by a disking or finishing tool to break clods and level the soil. Fall tillage occurred about 2 wk after the first killing frost, and spring tillage occurred at the earliest practical time the soil was fit for equipment operation (Table 1). A maturity group II, glyphosate-tolerant soybean variety was planted in all plots when soil temperatures at 5 cm exceeded 10 C. For plots that were not tilled in spring, glyphosate herbicide (0.84 kg ae ha^{-1}) was applied 3 to 8 d before planting. Soybeans were planted with a "Great Plains" no-till drill with 18-cm row spacing, calibrated to deliver 600,000 seeds ha^{-1} in plots 6.1 m wide and 15.2 m long.

Seedling emergence was counted immediately before spring tillage operations and weekly thereafter through the growing season. Giant foxtail seedlings were identified, counted, and removed from eight permanent quadrats (30 by 30 cm) plot^{-1}; quadrat locations were randomized each year.

Phenological Monitoring. Methods used for monitoring phenology of ornamental plants in this study have been described by Herms (1998, 1999, 2002). Briefly, we recorded the flowering phenology of 74 taxa of woody ornamental plants in the Secrest Arboretum on the OARDC campus. Plant species and cultivars were selected for their ease in identification and to represent a range of blooming times from early March through late July. This period overlaps with the emergence and management timing for giant foxtail. Four individuals of each ornamental species or cultivar were monitored. Although the protocol for giant foxtail emergence was designed to characterize the phenology of the entire population in the experimental field, methods used to monitor ornamental plant phenology were designed to minimize variation to increase predictive power. Therefore, to standardize for microenvironmental variation, all monitored plants were located in full sun and away from heat sources and sinks, such as buildings and parking lots. Plants were monitored daily for dates of first bloom and full bloom because these phenological events can be identified with precision. First bloom was defined as the date on which the first flower bud on the plant opened, revealing pistils or

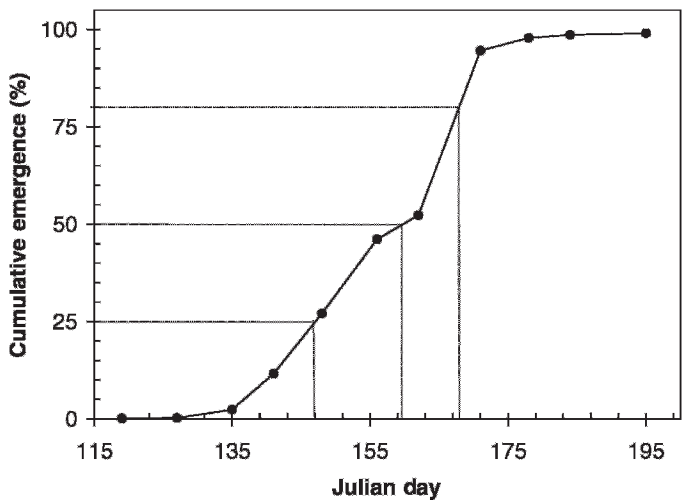

Figure 1. Cumulative emergence (%) of giant foxtail by Julian day in 1997. Lines show how Julian day for 25, 50, and 80% emergence were interpolated from the emergence curve.

stamens. Full bloom was defined as the date on which 95% of the flower buds had opened (i.e., 1 bud out of 20 had yet to open).

The OARDC weather station, also located in Secrest Arboretum, recorded air temperature, soil temperature, rainfall, and other standard measurements. GDD were calculated from daily maximum and minimum temperatures according to the modified sine wave approximation method (Allen 1976). The number of GDD accumulated for each ornamental plant phenological event was determined using a standard base temperature of 10 C and a January 1 starting date (Preuss 1983).

For giant foxtail emergence phenology, we selected 25, 50, and 80% emergence as critical phenological events with management significance. It is generally not possible to recognize when the first emergence occurs because this depends on sample area; therefore, we reasoned that a grower would want to know when 25% of the season's emergence had occurred, as a last reasonable time to apply PRE herbicides or to prepare for cultivation or other management measures. Although emergence is not symmetrical about 50% emergence (Forcella et al. 2000), this phenological event represents a hypothetical midpoint in emergence that might signal a time for scouting to map infested areas or in anticipation of postemergence treatment. When 80% of potential emergence has occurred, it is reasonable to expect that tillage or POST herbicide applications will be effective against most of the weed seedlings likely to appear in the crop.

Because the progress of emergence could only be determined at the end of the season, and emergence data were obtained from once-per-week counts that did not necessarily correspond to the target emergence percentages, it was necessary to interpolate from emergence curves to estimate the Julian days (sequentially numbered days of the year) for these phenological events. We estimated the JD of 25, 50, and 80% emergence by linear interpolation between surrounding points (Figure 1). We used a repeated-measures ANOVA to evaluate variation in interpolated JD values for 25, 50, and 80% emergence among tillage treatments, years, and their interaction. Interaction plots revealed no biologically significant trends. An ANOVA was conducted on data for individual years to determine whether emergence models could be developed using combined treatments or separate models for different tillage treatments.

Emergence Prediction Methods. *Julian Day.* To predict giant foxtail emergence in 2001, the arithmetic average JD over 1997 to 2000 was calculated for the emergence events in each tillage treatment. This represents the simplest of the four models and assumes that, on average, a given emergence event will occur on about the same JD each year.

Growing Degree–day. For each weed-emergence phenological event, we used air temperature to calculate cumulative GDD for each year (1997 to 2000) and tillage treatment. The Forecaster degree–day program (Ascerno and Moon 1989) was used to determine the combination of base temperature (lower developmental temperature threshold) and starting date that provided the best least-squares fit (Akers and Nielsen 1984; Arnold 1959, 1960). We evaluated three starting dates (October 1 of the previous year, January 1, and March 1) and six base temperatures (0 to 5 C). Air, and not soil, temperature was used because these data are more accessible to growers (Preuss 1983). To predict the JD for target emergence events in 2001, we calculated the average cumulative GDD (using the optimal base temperature and starting date combination) corresponding to each event in 1997 to 2000 and determined the JD on which that number of GDD had accumulated in 2001.

WeedCast. Dates of 25, 50, and 80% emergence for 2001 were predicted using the WeedCast model (Archer et al. 2001). Air temperature, soil temperature, and rainfall for 2001 were entered into WeedCast, along with relevant soil property information and tillage and planting time, to generate emergence curves from which estimated dates of emergence were determined. Simulation start dates and the initiation of seedling emergence accumulation corresponded to dates of tillage or glyphosate application (Table 1).

Phenological Calendar. A phenological calendar was constructed, consisting of the average chronological sequence of 45 phenological events for 23 of the ornamental species monitored from 1997 to 2000 (Herms 1998, 1999, 2002). This subset represents species and varieties that are most common and easy to identify. The phenological sequence was shown to be highly constant from year to year, even with substantial annual variation in patterns of degree–day accumulation (Herms 2002, 2004), and consistently surrounded the target emergence events for giant foxtail. Targeted weed emergence events from 1997 to 2000 were inserted into the phenological calendar based on their date of occurrence each year relative to first and full bloom of the ornamental plants.

To use an ornamental plant phenological event as a predictor of a particular giant foxtail emergence event, we chose the plant event that, on average, occurred in the phenological sequence just before (or on the same day as) the weed event, and determined the predicted day to be the average number of days after the predictor event that the weed event occurred. For example, if first bloom of multiflora rose (*Rosa multiflora* Thunb. ex Murr.) occurred an average of 3 d before the weed event from 1997 to 2000, then the predicted

Table 2. Results of ANOVA for Julian day of 25, 50, and 80% emergence of giant foxtail in 1997. Analyses were conducted by year to test the main effects and interaction of tillage treatments on Julian day of target emergence events.[a]

Cumulative emergence	Source	df[a]	Type III SS	Mean square	F	Pr > F[d]
%						
25	Replication	4	155.0	38.8	1.17	0.37
	Fall tillage	1	92.5	92.5	2.80	0.12
	Spring tillage	1	22.1	22.1	0.67	0.43
	Fall × spring tillage	1	76.1	76.1	2.30	0.16
50%	Replication	4	198.7	49.7	2.02	0.16
	Fall tillage	1	76.1	76.1	3.09	0.10
	Spring tillage	1	2.5	2.5	0.10	0.76
	Fall × spring tillage	1	130.1	130.1	5.28	0.04
80%	Replication	4	18.8	4.7	1.88	0.18
	Fall tillage	1	1.8	1.8	0.72	0.41
	Spring tillage	1	0.0	0.0	0.00	1.00
	Fall × spring tillage	1	7.2	7.2	2.88	0.12

[a] Abbreviations: df, degrees of freedom; SS, sum of squares associated with type III estimable functions; F, the ratio of the mean square divided by the mean square for error, for testing the null hypothesis that the group means for that effect are equal; Pr > F, the probability value associated with the F value.; Rep, DEFINITION

day of the weed event in 2001 was 3 d after the date on which multiflora rose was observed to bloom.

Comparison of Prediction Methods. We assessed the overall accuracy of the phenological calendar by plotting the average rank order of phenological events from 1997 to 2000 against the rank order of those same events in 2001 and evaluating the fit to the 1 : 1 regression line. Using 2001 emergence data, we compared the accuracy of the phenological calendar predictions with those based on average JD from 1997 to 2000 and cumulative GDD from 1997 to 2000 as well as dates of phenological events predicted by WeedCast by looking at the magnitude of the deviations in observed vs. predicted dates for each emergence event.

Results and Discussion

Effects of Tillage. An ANOVA of interpolated JD values for the target stages of foxtail emergence (25, 50, and 80% emergence) for 1997 through 2000 revealed no significant differences among the main effects of fall and spring tillage treatments (Table 2, data for 1997 only). There was an interaction ($P < 0.04$) between fall and spring tillage treatments in 1997 for 50% emergence (Table 2).

Examination of emergence curves for all years and treatments suggested a possible biologically significant difference among the patterns of emergence for treatments with and without fall tillage. Therefore, we combined treatments with and without fall tillage and evaluated separate models to describe emergence in those treatment combinations along with a combined model for all treatments. Hereafter, these are designated as (1) fall tillage, for plots that were chisel plowed in fall (plots with fall tillage only and fall tillage plus spring tillage); (2) no fall tillage, for plots that were not plowed in fall (plots with spring tillage only and neither fall nor spring tillage); and (3) fall plus no fall tillage, for all treatments combined. The fall tillage and no fall tillage treatments represent practical differences in the way most local crop fields are managed. Biologically, these two scenarios represent different overwintering environments. That is, mixing of seeds into the soil in fall compared with seeds left on the soil surface might induce physiological differences that would result in different emergence patterns.

Emergence Prediction Methods. ***Julian day*****.** The JD method indicates the average JD on which the target level of emergence might be expected. The average JDs for 25, 50, and 80% emergence for the combined tillage treatment were 131, 136, and 160 (Table 3), which correspond to May 11, May 16, and June 9 in 2001. These represent a realistic rule of thumb for the target emergence events but would not be expected to be accurate in years of unusual weather conditions. The maximum variation in JD among tillage treatments was 1, 2, and 11 d for 25, 50, and 80% emergence, respectively, suggesting that the general guidelines might be more useful for early emergence events, which are controlled mostly by temperature, than for later events, which are influenced by soil moisture as well as temperature (Roberts and Potter 1980; Stoller and Wax 1973).

Growing Degree–day. To choose the ''best'' GDD model for predicting the target emergence stages, it was necessary to select both a base temperature and a start date for degree–day accumulation. The combination of start date and base temperature that gives the lowest variation over years in cumulative GDD should result in the most reliable model for predicting emergence based on heat units (Herms et al. 2004; Higley et al. 1986). We used the 1997 to 2000 data to select a model that generally produced the lowest coefficient of variation (CV) for cumulative GDD at the target emergence stages (Table 4).

CVs were lowest when the October 1 start date from the previous year was used in degree–day models to describe all emergence events tested. The CVs for the October start date ranged from 4.2 to 14.5 and were about 13 to 22 units lower than January or March start dates at corresponding base temperatures (Table 4). Forcella et al. (2000) reported substantial site differences in prediction of green foxtail [*Setaria viridis* (L.) Beauv.] emergence across five states because of instability of ideal base temperatures and cumulative GDD among seed populations, but in all cases the starting date tested was January 1. The lack of fit between thermal time and emergence has been attributed to soil water limitations (King and Oliver 1994), but our results suggest that choosing an appropriate starting date might also be a factor.

In 20 of the 27 scenarios tested, the base temperature that resulted in the lowest CV was 0 C (Table 4). In cases where

Table 3. Predicted Julian days of 25, 50, and 80% emergence of giant foxtail seedlings using four prediction methods for field plots with fall tillage, no fall tillage, or all treatments combined. Julian day, cumulative growing degree–day, and phenological calendar predictions were based on emergence data from 1997 to 2000; WeedCast predictions were based on local soil and environmental data from 2001.[a]

Treatment combination	Cumulative emergence	Prediction Methods				
				WeedCast		
		JD	GDD	Chisel	NT	Phenological calendar
	%	Predicted JD				
Fall tillage[b]	25	132	137	131	136	127
No fall tillage[c]	25	131	137	131	136	126
Fall + no fall tillage	25	131	137	131	136	127
Fall tillage	50	136	143	138	141	129
No fall tillage	50	138	146	138	141	132
Fall + no fall tillage	50	136	142	138	141	128
Fall tillage	80	151	160	150	154	146
No fall tillage	80	161	168	150	154	162
Fall + no fall tillage	80	160	167	150	154	163

[a] Abbreviations: JD, Julian Days; GDD, growing degree–days; NT, no till.
[b] Includes plots for the two treatments: fall tillage only and fall tillage plus spring tillage.
[c] Includes plots for the two treatments: spring tillage only and neither fall nor spring tillage.

the CV was lower at other base temperatures, there was only a 0.1 to 3.3 unit deviation from the CV at 0 C. The choice of 0 C as the base temperature may appear unrealistic because laboratory studies have shown that giant foxtail seeds do not germinate below 5 C (Leon et al. 2004; Mester and Buhler 1991), and field studies have suggested that emergence begins when soil temperatures exceeded 10 C (Moore and Fletchall 1963). However, when linear degree–day models are used to model phenological events, which typically respond non-linearly to temperature, they usually generate base temperatures that differ from the lower temperature threshold (Higley et al. 1986). This is not considered a problem when the primary objective is to generate a heuristic tool for predicting pest phenology in the field rather than to model true physiological responses to temperature (Higley et al. 1986; Snyder et al. 1999). Because low temperatures (~ 5 C) are thought to promote afterripening in dormant giant foxtail seeds (Dekker et al. 1996; Stanway 1971), a model with 0 C base temperature and GDD accumulation beginning in October may have biological as well as predictive relevance

Table 4. Coefficients of variation (CV) for degree–day models with different start dates and base temperatures that predict 25, 50, and 80% cumulative emergence of giant foxtail from 1997 to 2000 (lowest CVs per start date are in bold) in field plot treatments with and without fall tillage or all treatments combined.

Treatment combination	Cumulative emergence	Start date	Coefficients of variation for base temperatures (C)					
			0	1	2	3	4	5
	%		%					
Fall tillage[a]	25	1-Oct[c]	**7.5**	7.8	8.2	8.6	8.9	9.3
No fall tillage[b]	25	1-Oct	**7.2**	7.3	7.4	7.6	7.8	7.9
Fall + no fall tillage	25	1-Oct	**4.2**	4.5	4.9	5.3	5.7	6.1
Fall tillage	25	1-Jan	**21.4**	22.0	22.5	22.9	23.2	23.3
No fall tillage	25	1-Jan	**22.3**	22.8	23.3	23.6	23.9	23.9
Fall + no fall tillage	25	1-Jan	**14.5**	14.7	14.9	15.0	14.9	14.7
Fall tillage	25	1-Mar	27.3	27.3	27.1	26.9	26.5	**25.9**
No fall tillage	25	1-Mar	28.8	28.8	28.7	28.5	28.2	**27.8**
Fall + no fall tillage	25	1-Mar	18.4	18.0	17.5	17.0	16.3	**15.4**
Fall tillage	50	1-Oct	5.3	**5.2**	**5.2**	5.3	5.4	5.5
No fall tillage	50	1-Oct	**10.6**	11.0	11.3	11.8	12.2	12.6
Fall + no fall tillage	50	1-Oct	**6.0**	6.4	6.8	7.1	7.5	7.8
Fall tillage	50	1-Jan	**16.8**	17.1	17.3	17.5	17.7	17.8
No fall tillage	50	1-Jan	**20.2**	20.7	21.2	21.7	22.2	22.7
Fall + no fall tillage	50	1-Jan	10.7	10.7	10.7	10.7	10.6	**10.4**
Fall tillage	50	1-Mar	**19.5**	**19.5**	19.6	19.6	19.8	19.9
No fall tillage	50	1-Mar	27.5	27.6	27.6	27.6	27.5	**27.4**
Fall + no fall tillage	50	1-Mar	15.6	15.1	14.6	13.9	13.2	**12.3**
Fall tillage	80	1-Oct	**11.5**	11.9	12.4	13.0	13.7	14.5
No fall tillage	80	1-Oct	**6.5**	6.6	6.7	6.9	7.2	7.6
Fall + no fall tillage	80	1-Oct	**7.5**	8.0	8.6	9.2	9.9	10.6
Fall tillage	80	1-Jan	**23.7**	24.3	25.0	25.8	26.5	27.4
No fall tillage	80	1-Jan	**15.8**	16.0	16.3	16.6	17.0	17.5
Fall + no fall tillage	80	1-Jan	**13.0**	13.5	14.0	14.6	15.1	15.7
Fall tillage	80	1-Mar	**25.6**	26.3	27.1	28.0	29.0	30.1
No fall tillage	80	1-Mar	**17.3**	17.6	18.0	18.6	19.2	19.9
Fall + no fall tillage	80	1-Mar	**13.1**	13.5	14.0	14.6	15.2	15.9

[a] Includes plots for the two treatments: fall tillage only and fall tillage plus spring tillage.
[b] Includes plots for the two treatments: spring tillage only and neither fall nor spring tillage.
[c] October 1 start date begins in the year before January 1 and March 1 start dates.

because physiological changes leading to seedling emergence are likely to begin with temperature-dependent processes that occur the previous autumn.

Using the 0 C base temperature and October 1 start date, we plotted the cumulative GDD for each year (Figure 2). The patterns for the 4 yr (1997 to 2000) used for model development varied in the rate of heat-unit accumulation, with 1,725, 2,058, 2,129, and 2,165 GDD accumulated by July 1 for 1997, 1998, 1999, and 2000, respectively. An El Niño event occurred in the spring of 1998, which generated a surge in cumulative GDD between March 26 and March 31 when temperatures reached at least 23.9 C every day (Figure 2). The validation year (2001) was somewhat unusual in having greater GDD accumulation the previous fall and delayed warming in early spring, but summer temperatures were about average, with 1,858 GDD accumulated by July 1 (Figure 2).

The predicted JDs for 25, 50, and 80% emergence based on GDD were 137, 142, and 167 for the combined tillage treatment (Table 3), respectively, which correspond to May 17, May 22, and June 16 in 2001. The maximum variation in predicted JD among tillage treatments was 0, 4, and 8 d for 25, 50, and 80% emergence, respectively.

WeedCast. The WeedCast model was run using the same temperature data that were used for the GDD model and phenological calendar in 2001. Soil data were entered for a silt-loam soil, and it was assumed that soil was saturated in spring, which is generally the case and especially true for the 2001 growing season. The model does not differentiate among variables such as fall tillage treatments. Simulations for the chisel-plow treatment commenced on April 20 (tillage date), and those for the nontilled treatment on April 27 (burn-down herbicide application date). From the emergence curve and associated tabular data generated by the model, we determined the predicted JD of the target emergence events. The WeedCast simulations for the chisel-plow treatment predicted 25, 50, and 80% emergence on JD 131, 138, and 150 (Table 3), respectively, which corresponds to May 11, May 18, and May 30 in 2001. For the nontilled treatment, predicted JDs for 25, 50, and 80% emergence were 136, 141, and 154, or May 16, May 21, and June 3, respectively.

Phenological Calendar. The phenological calendar of 45 ornamental plant bloom events and nine giant foxtail emergence events is shown in Table 5. For all three field treatment combinations (fall tillage, no fall tillage, and all combined), 25% emergence occurred consistently after the first 13 ornamental plant bloom events. We expected this early emergence event to be the most easily predicted because soil moisture is generally not limiting at this time, so early emergence is mostly dependent on temperature. Over 1997 to 2000, 50% emergence occurred 10 bloom events after 25% emergence for the fall tillage plots and all plots combined, and 13 bloom events after 25% emergence for the no fall tillage plots. The placement of 80% emergence of the three giant foxtail treatment combinations in the phenological calendar showed the most variation, with giant foxtail emergence being the 41st, 47th and 49th event for fall tillage plots, no fall tillage plots and all combined plots, respectively, a difference of 2 to 8 d. The greater variation among tillage treatments in the timing of later emergence events might be related to differences in physiological status of seeds in soil that has been tilled versus not tilled in the fall. Reasons for why seeds buried by fall tillage would reach 80% emergence earlier than those left on the surface are not clear at this time.

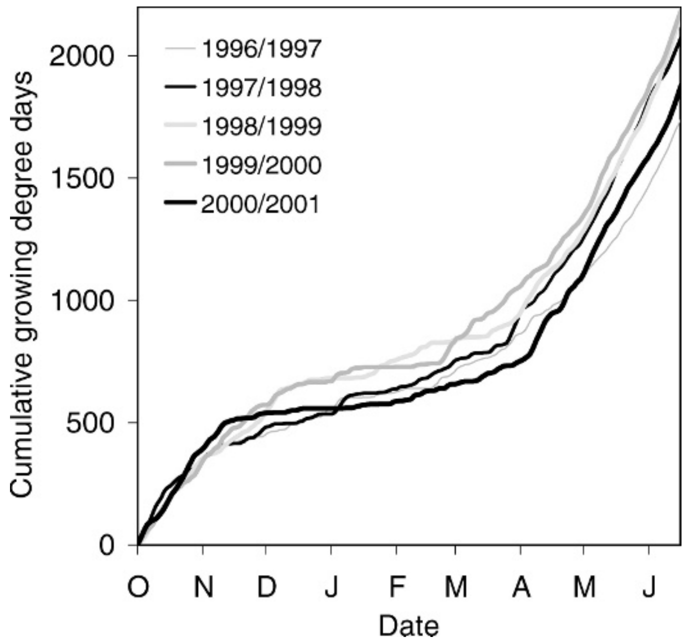

Figure 2. Patterns of growing degree–day accumulation beginning October 1 (0 C base temperature) for the years used to develop the phenological calendar (1996 to 1997 through 1999 to 2000) and for the validation year (2000 to 2001).

For the combined tillage treatment, the phenological calendar predicted 25% emergence to occur on JD 127, using red chokeberry [*Aronia arbutifolia* (L.) Pers.] as the phenological predictor; 50% emergence to occur on JD 128, using Ohio buckeye (*Aesculus glabra* Willd.); and 80% emergence to occur on JD 163, using northern catalpa [*Catalpa speciosa* (Warder ex Barney) Warner ex Engelm.], which corresponds to May 7, May 8, and June 12 in 2001, respectively (Tables 3 and 5). The maximum variation in JD among treatments for 25, 50, and 80% emergence was 1, 4, and 17 d, respectively. This approach predicted 25% emergence 4 to 5 d earlier than the JD method and WeedCast (chisel model) and 10 to 11 d earlier than the GDD method, whereas the 80% emergence prediction was about halfway between the JD and GDD predictions. For the fall tillage and combined tillage treatments, the phenological calendar predicted that 50% emergence would occur only 1 to 2 d after 25% emergence, which is possible in a period of relatively high temperatures, but probably not realistic in most years.

Comparison of Prediction Methods. The use of the phenological sequence to predict pest activity assumes that ornamental plant flowering and weed emergence occur in about the same order each year. One way to visualize the consistency of the phenological sequence is to plot the average ranking of events for 1997 to 2000 against the ranking in the validation year 2001. Figure 3 shows the 4-yr average rank order of 54 phenological events and the rank order for those events in 2001 along the 1 : 1 line. Even with substantial annual variation among years in patterns of GDD accumulation (Figure 2), there was little variation in the order in which plants bloomed and giant foxtail reached specific stages

Table 5. Phenological calendar for ornamental plant bloom events (first and full) and giant foxtail emergence events (25, 50, and 80%). Data are average calendar dates and cumulative growing degree–days (GDD) (January 1 start date, 10 C base temperature) for 1997 to 2000 and actual dates and GDD in 2001. Events are sorted by the average GDD from 1997 to 2000. Giant foxtail emergence is averaged over field plot treatments by fall tillage, no fall tillage, or all treatments combined.

Common name	Scientific name or tillage treatment	Event or % emergence	Average occurrence 1997–2000		Occurrence in 2001	
			Date	GDD	Date	GDD
Eastern redbud	*Cercis canadensis* L.	First bloom	24-Apr	198	21-Apr	162
Snowdrift crabapple	*Malus* 'Snowdrift'	First bloom	24-Apr	202	22-Apr	181
Wayfaringtree viburnum	*Viburnum lantana* L.	First bloom	29-Apr	228	29-Apr	232
Tatarian honeysuckle	*Lonicera tatarica* L.	First bloom	30-Apr	231	30-Apr	241
Common lilac	*Syringa vulgaris* L.	First bloom	1-May	235	29-Apr	232
Persian lilac	*Syringa* × *persica* L.	First bloom	2-May	240	30-Apr	241
Snowdrift crabapple	*Malus* 'Snowdrift'	Full bloom	3-May	248	1-May	255
Ohio buckeye	*Aesculus glabra* Willd.	First bloom	3-May	250	27-Apr	224
Eastern redbud	*Cercis canadensis* L.	Full bloom	4-May	252	26-Apr	217
Common horse-chestnut tree	*Aesculus hippocastanum* L.	First bloom	5-May	256	29-Apr	232
Blackhaw viburnum	*Viburnum prunifolium* L.	First bloom	6-May	269	2-May	272
Flowering dogwood	*Cornus florida* L.	First bloom	6-May	272	1-May	255
Red chokeberry	*Aronia arbutifolia* (L.) Pers.	First bloom	7-May	279	3-May	289
Giant foxtail	**No fall tillage**[a]	25%	10-May	286	8-May	364
Giant foxtail	**Fall + no fall tillage**	25%	11-May	288	7-May	352
Giant foxtail	**Fall tillage**[b]	25%	11-May	290	5-May	324
Wayfaringtree viburnum	*Viburnum lantana* L.	Full bloom	8-May	291	3-May	289
Persian lilac	*Syringa* × *persica* L.	Full bloom	9-May	296	6-May	337
Vanhoutte spirea	*Spiraea* × *vanhouttei* (Briot) Carr.	First bloom	10-May	305	5-May	324
Common lilac	*Syringa vulgaris* L.	Full bloom	10-May	313	5-May	324
Blackhaw viburnum	*Viburnum prunifolium* L.	Full bloom	10-May	319	6-May	337
Winter king hawthorn	*Crataegus viridis* L.	First bloom	12-May	329	5-May	324
Common horse-chestnut tree	*Aesculus hippocastanum* L.	Full bloom	13-May	344	7-May	352
Red chokeberry	*Aronia arbutifolia* (L.) Pers.	Full bloom	13-May	351	7-May	352
Black cherry	*Prunus serotina* Ehrh.	First bloom	14-May	369	8-May	364
Ohio buckeye	*Aesculus glabra* Zab.	Full bloom	15-May	377	8-May	364
Giant foxtail	**Fall + no fall tillage**	50%	15-May	380	12-May	415
Giant foxtail	**Fall tillage**	50%	16-May	382	10-May	387
Vanhoutte spirea	*Spiraea* × *vanhouttei* L.	Full bloom	17-May	402	14-May	423
Winter king hawthorn	*Crataegus viridis* L.	Full bloom	17-May	404	14-May	423
Tatarian honeysuckle	*Lonicera tatarica* L.	Full bloom	18-May	409	12-May	415
Giant foxtail	**No fall tillage**	50%	18-May	413	17-May	451
Black cherry	*Prunus serotina* Ehrh.	Full bloom	19-May	419	13-May	419
Black locust	*Robinia pseudoacacia* L.	First bloom	22-May	471	17-May	451
Common ninebark	*Physocarpus opulifolius* (L.) Maxim.	First bloom	23-May	481	18-May	467
Sweet mock-orange	*Philadelphus coronarius* L.	First bloom	23-May	483	19-May	478
Arrowwood viburnum	*Viburnum dentatum* L.	First bloom	28-May	533	25-May	538
Black locust	*Robinia pseudoacacia* L.	Full bloom	28-May	550	25-May	538
Multiflora rose	*Rosa multiflora* Thunb. ex Murr.	First bloom	29-May	554	25-May	538
Mountain laurel	*Kalmia latifolia* L.	First bloom	29-May	557	2-Jun	598
Giant foxtail	**Fall tillage**	80%	30-May	578	19-May	478
Common ninebark	*Physocarpus opulifolius* (L.) Maxim.	Full bloom	31-May	592	4-Jun	610
Arrowwood viburnum	*Viburnum dentatum* L.	Full bloom	3-Jun	624	4-Jun	610
Multiflora rose	*Rosa multiflora* Thunb. ex Murr.	Full bloom	3-Jun	645	8-Jun	654
Washington hawthorn	*Crateagus phaenopyrum* (L. f.) Medik	First bloom	4-Jun	645	2-Jun	598
Northern catalpa	*Catalpa speciosa* (Warder ex Barney)	First bloom	5-Jun	677	9-Jun	666
Giant foxtail	**Fall + no fall tillage**	80%	8-Jun	693	29-May	568
American elder	*Sambucus canadensis* L.	First bloom	8-Jun	714	10-Jun	681
Giant foxtail	**No fall tillage**	80%	9-Jun	717	16-Jun	832
Sweet mockorange	*Philadelphus coronarius* L.	Full bloom	7-Jun	721	11-Jun	704
Washington hawthorn	*Crateagus phaenopyrum* (L. f.) Medik	Full bloom	9-Jun	748	9-Jun	666
Northern catalpa	*Catalpa speciosa* (Warder ex Barney)	Full bloom	12-Jun	808	17-Jun	850
Mountain laurel	*Kalmia latifolia* L.	Full bloom	14-Jun	826	15-Jun	809
American elder	*Sambucus canadensis* L.	Full bloom	18-Jun	913	19-Jun	892

[a] Includes plots for the two treatments: spring tillage only and neither fall nor spring tillage.
[b] Includes plots for the two treatments: fall tillage only and fall tillage plus spring tillage.

of emergence. The rank order was very consistent among years ($R^2 = 0.96$) for ornamental plant phenology and giant foxtail emergence events (Figure 3) and shows that weed emergence events ranked as consistently as ornamental plant flowering. The highest deviation was for 25% emergence in the no fall tillage plots, whereas for the fall-tillage plots the emergence sequence fell on the 1 : 1 line for 25 and 50% emergence, with only a slight deviation for 80% emergence.

We compared the accuracy of the four methods for predicting the timing of 25, 50, and 80% emergence in 2001. Table 6 shows the deviation in JD of the various prediction approaches from the actual day of the emergence event in 2001. For all emergence events in the three tillage treatment combinations, the date predicted by GDD was always later than the actual date, by 1 to 21 d (average deviation = 11.4 d). The JD approach was more accurate, a result that was

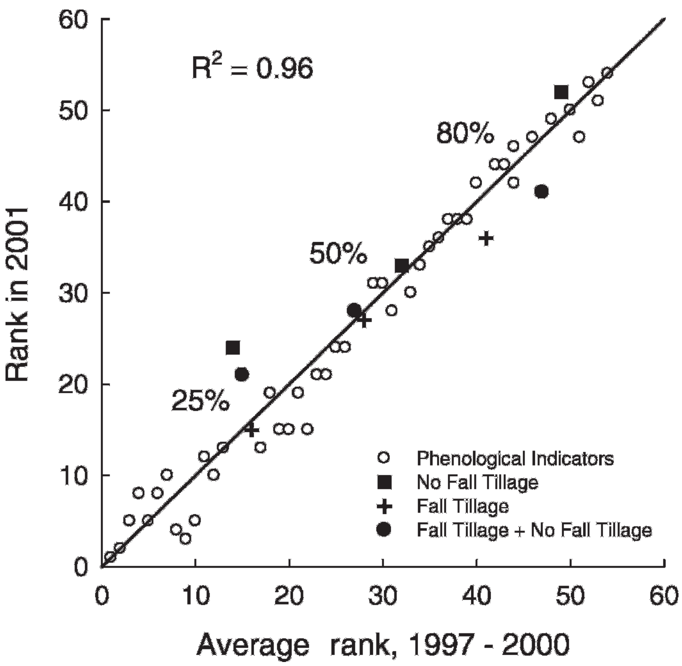

Figure 3. Correspondence between 4-yr average rank order (1997 to 2000) and the rank order in 2001 of phenological events for 23 ornamental plants ("phenological indicators") and 25, 50, and 80% emergence of giant foxtail in field plots with fall tillage, no fall tillage, or all treatments combined, along the 1 : 1 line of correspondence.

not expected, with the predicted date 1 to 3 d later or 6 d before the actual date (average deviation = 6.0 d). Although predictions using GDD or JD were generally better for the no fall tillage plots than for fall-tillage plots or all plots combined, the relatively poor performance of the GDD approach suggests that linear models based on air temperature are not well correlated with actual physiological responses regulating foxtail germination. Using mean absolute deviations as a criterion for assessing quality of estimates, the WeedCast predictions were generally better than those from the GDD approach, equivalent to simple Julian days, and less accurate than the phenological calendar method. The phenological calendar tended to predict emergence after the actual date, whereas the other methods tended to predict emergence too early. Overall, predictions using the phenological calendar were closer to the actual dates of emergence (average deviation = 4.4) than the other prediction methods.

Grouping the data from plots with either fall tillage or no fall tillage allowed us to evaluate whether separate models for emergence prediction need to be developed for specific soil management scenarios, or whether a combined model that ignores tillage treatments would provide equivalent predictions. Models developed for the two tillage treatments predicted 25% emergence within 2 d using the phenological calendar, whereas the combined model predicted this event exactly (Table 6). A 2-d deviation in prediction is probably not meaningful biologically or in a practical sense. However, for 80% emergence, the predictions from the three models were quite divergent (5 d after, or up to 14 d before). For other prediction tools, emergence was generally predicted better for the no-fall-tillage data than the fall-tillage data or the combined model. However, WeedCast gave a more accurate prediction for 80% emergence using the combined data set than other prediction tools.

Utility of Phenological Calendar. The utility of the phenological calendar is that it provides information on the *order* of events rather than just predicting the time of occurrence of a specific event; therefore, the calendar is most useful for following the progress of biological events to anticipate and plan for the optimum timing of management strategies (Herms 2004). For example, using the phenological calendar, a grower might anticipate the early emergence stages of giant foxtail by monitoring first bloom of the species in Table 5. When common lilac (*Syringa vulgaris* L.) starts to bloom, a grower should begin to prepare control measures for giant foxtail, and a good target date for PRE herbicide application would be around the time of eastern redbud (*Cercis canadensis* L.) first bloom. When red chokeberry has reached the first bloom stage, about 25% of the giant foxtail seedlings will have emerged, and the application of a PRE herbicide at this time likely will not be effective against this proportion of the giant foxtail population. It is also too early at this point to apply a POST herbicide because about 75% of the potential giant foxtail population has yet to emerge. About the time multiflora rose reaches full bloom, growers should

Table 6. Observed emergence dates (JD) in 2001 and deviation of observed dates from dates predicted by four methods to estimate 25, 50, and 80% emergence of giant foxtail seedlings in field plots with fall tillage, no fall tillage, or all treatments combined.[a]

Treatment combination	Cumulative emergence	Observed 2001	Prediction methods: JD	GDD	WeedCast: Chisel	WeedCast: No-till	Phenological calendar
	%	JD	Deviation (Observed JD - predicted JD)				
Fall tillage[b]	25	125	−7	−12	−6	−11	−2
No fall tillage[c]	25	128	−3	−9	−3	−8	2
Fall + no fall tillage	25	127	−4	−10	−4	−9	0
Fall tillage	50	130	−6	−13	−8	−11	1
No fall tillage	50	137	−1	−9	−1	−4	5
Fall + no fall tillage	50	132	−4	−10	−6	−9	4
Fall tillage	80	139	−12	−21	−10	−15	−7
No fall tillage	80	167	6	−1	18	13	5
Fall + no fall tillage	80	149	−11	−18	0	−5	−14
Average deviation[d]			6.0	11.4	6.3	9.4	4.4

[a] Abbreviations: JD, Julian days; GDD, growing degree–days.
[b] Includes plots for the two treatments: fall tillage only and fall tillage plus spring tillage.
[c] Includes plots for the two treatments: spring tillage only and neither fall nor spring tillage.
[d] Average deviation is the sum of deviations (absolute value) divided by the number of cases (n = 9).

anticipate the stage when about 80% of giant foxtail seedlings have emerged, and they should be prepared to apply a POST herbicide or cultivate. Timing herbicide applications to target the young seedling emergence stage can allow growers to use lower rates of herbicides to kill weeds like giant foxtail (Harker and O'Sullivan 1991; Morrison and Maurice 1984).

Several sources of error are important to consider in developing the phenological calendar for weed emergence. For example, it is often difficult to determine when emergence begins and ends. The larger the field and the more intense the scouting effort, the more likely one is to find a uniquely early or late-emerging seedling. It is only after the data are plotted for a given growing season that a particular target emergence event (e.g., 25% emergence) can be determined. Moreover, weed seedling emergence is the final stage of a complicated process that includes loss of dormancy, water imbibition, germination, and initial seedling growth before the emerged seedling appears above the soil surface (Vleeshouwers and Kropff 2000). At most of these steps, weed seeds and seedlings respond to soil temperature, whereas air temperature probably is a more important driver for ornamental plant flowering phenology. The weed seeds that give rise to a seedling population are distributed in the soil from the surface to several cm below the surface, with a steep temperature gradient in this zone, a microenvironment that probably has little impact on ornamental plant blooming. No model currently takes account of this temperature gradient with soil depth.

The various steps that lead to emerged weed seedlings are dependent on moisture as well as temperature. The strength of WeedCast over the other prediction methods is that it accounts for soil moisture in the upper 5 cm of soil and does not advance emergence unless soil water potential is above a threshold (Archer et al. 2001). However, it currently does not account for gradients of soil water with depth. The GDD and JD methods have no way to account for soil moisture variation. The phenological calendar method assumes that the flowering phenology of ornamental plants is a function of temperature, as is weed emergence, but the impact of water stresses on woody plant flowering is likely to be less immediate and less critical than the corresponding impact on seed germination and seedling emergence. Therefore, an unusually dry period is likely to interrupt the seedling emergence process while ornamental plant flowering continues, thereby introducing errors through this manner of emergence prediction. Nevertheless, such errors were not apparent in the period of the present study.

In summary, our data indicate a consistent pattern in the order of giant foxtail emergence events that corresponds well with the order of ornamental plant flowering, which allowed for predictions of sufficient accuracy for use in optimizing the timing of weed scouting and management procedures. A phenological calendar can be an important tool in an integrated approach for emergence prediction, to be used in conjunction with web-based models (e.g., http://www.oardc.ohio-state.edu/gdd/), supported by local verification of ornamental plant phenology.

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